UTILIZING SEISMIC/ACOUSTIC SENSORS TO PROTECT SECURE FACILITIES FROM UNDERGROUND INTRUSION

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ABSTRACT

A seismic/acoustic array was developed to detect activity in clandestine tunnels. The geologic setting of the area that encloses clandestine tunneling activity can preclude use of traditional tunnel-detection technologies such as ground-penetrating radar (GPR). Properties of the sediments at the study site are attributable to original environment of deposition and subsequent natural and human-caused modifications. The resulting lateral and vertical variability in critical soil properties confounded GPR and electromagnetic techniques, but did not appear to have a negative impact on propagation of seismic/acoustic signals from digging and movement within a test tunnel. The team developed algorithms that distinguish the signals from digging and human movement from those of surface activity. Prolonged rainfall at the tunnel site caused an increase in signal amplitude, and allowed the team to quantify the signal changes from the full range of mechanical and Soldier noise on a Forward Operating Base (FOB). Understanding the impacts of variability in soil density, moisture content, and grain size may allow further refinement of the algorithm.

INTRODUCTION

The need to detect tunnels penetrating secure facilities (e.g., detention centers, borders, or weapons storage areas) has grown from exploitation along the Southern US border, Iraq, and other facilities. The US Army became involved in this enterprise as a result of a nearly successful escape from a tunnel constructed over several months by the detainees in an Iraqi center (Fanaru and Shadid, 2005).   In response to this incident, a team of researchers was sent to Iraq to investigate the use of several technologies that were believed to be able to detect voids as small as 1 meter in diameter. A third technology investigated was a passive seismic/acoustic array. The team built a 7-meter-deep tunnel at the same depth as the escape tunnel (Tucker and McKenna, 2006). The array was tested around the camp to garner the seismic and acoustic characteristics of the typical vehicles and machinery and their interactions with the soil and each other. The in-tunnel tests were conducted using typical digging tools available to the detainees . All of these signals were then used to "train" the computer algorithms.   This technology proved successful. Plans were laid for a larger implementation study and more detailed sediment and mineral studies. There is a need to understand the interaction between sound propagation and the local geology and geochemistry of the sediments.

SITE GEOLOGY

Distribution of mineral composition, grain size, and moisture content of soils are known to affect attenuation of electromagnetic and other geophysical sensor signals (Saarenketo, 1998; al Hagrey and Muller, 2000). The geologic setting of an area determines the suitability of a given technique for locating visually obscured features such as tunnels in the shallow subsurface.

In the area surrounding the test tunnel, the upper 6 meters of sediments were deposited as part of a delta during a time of higher sea level, when low-gradient rivers carried fine-grained sediments from a mixture of arid terrain and wetlands and deposited those sediments in a shallow sea. During deposition of the delta, distributary channels moved laterally over the area, resulting in changes in grain size and mineralogy both laterally and vertically over distances of a few meters or less. After deposition, the shallow sea receded and the delta complex became dry land. Subsequent natural and man-caused processes have altered the original distribution of grain size and mineralogy. Those changes include: centuries of agriculture that introduced soluble minerals in irrigation water and erased the original distinction of sediments by plowing in the upper meter of now-abandoned fields; movement of soluble minerals within the sediments with the addition and subtraction of soil moisture by precipitation and evaporation; and infilling of low areas with additional soil during recent construction. The ongoing action of wind has reworked the surface material and deposited a layer of silt and fine sand, consisting of very fine and well rounded quartz and feldspar grains with minor amounts of dark mineral

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grains. The resulting sediments include layers of water-laid silts and fine sands that vary in thickness, density, moisture content, and color both horizontally and vertically, overlain by similarly fine-grained wind-blown material.

The sediments are cemented locally with either calcium carbonate (calcite) or calcium sulfate (gypsum) at a depth of about 30 cm. Layers and lenses of cemented and non-cemented sediments vary in depth and vertical extent depending on the location within the camp (figure 1). In the upper layer the gypsum forms veinlets some 5 mm in diameter and spaced quite closely throughout the layer. Crystals of gypsum up to 3 cm in length were observed. The lower sediment layers are typically devoid of visible gypsum crystals, although the presence of discontinuous gypsum has been confirmed to a depth of 6 meters.

Figure 1. Typical strata sequence in the study area. Note the subtle lateral color changes and weathering profile differences.

At some locations in the study area near the surface, there are substantial areas of white cemented sand that is locally called "gatch" (see Figure 2). Gatch forms when carbonate or sulfate minerals (calcite or gypsum or both) are deposited by with movement and evaporation of water in the pore space of previously deposited sand (Shaqour 2007). When water is mixed with a 50/50 mixture of gatch and other surficial material an extremely hard block is formed. This material is used to make roads and hardened areas for construction in the local community.

At a depth of about 6.5 to 7 meters, a thick sequence of unconsolidated sand is encountered. This unconsolidated coarse sand (particles 2 mm diameter), composed of angular grains of quartz with accessory minerals, extends at least 1 meter below the tunnel floor. The sand layer has visibly cross-bedded and distinct sub-layers of coarse to fine sand, and may represent wind-blown dune sand that covered the region prior to sea-level advance and formation of the fine-grained delta.

Figure 2. A layer of gatch about 20 cm below the surface. This layer was about 10 cm thick.

This layer also includes black concretions that appear as very hard clusters of sand grains cemented in a star-burst pattern by a black mineral. These concretions are hard dark mineral clots found as radiating spheres of 1 to 3 cm in diameter. There are also up to 1 cm wide veinlets that normally extend less than 5 cm in length. These features are abundant in the upper part of the unconsolidated sand layer and are found in a reddish silt layer near the contact, which in some cases is more gradational than abrupt (figure 3). The overlying silt slumps into the sand layer at many locations. These hard mineral concretions are generally found within 30 cm of the contact and are sufficiently hardened that distinct impact sounds are generated when they are struck with an entrenching tool

Figure 3. Project leader for the initial site project, works through the black mineral concretions at the tunnel face. See arrows and line.

or chisel. The red color of the silt indicates that iron is present in the sediments. Iron-rich concretions are a fairly common feature in temperate desert areas, where iron available in porous sand combines with evaporation-driven water locally forming cemented and very hard sand clusters (Chan et al. 2004).

The extraordinary lateral and vertical variability of the sediments in the upper several meters of soil at the site caused the failure of traditional geophysical techniques to locate tunnels. Presence of fine-grained minerals and soluble salts increase the conductivity of the soil and preclude downward propagation of signals from methods such as ground-penetrating radar and electromagnetic surveys. In addition, the discontinuous bedding that resulted from deposition in a delta generated distinct soil bodies with a cross-sectional size similar to that of a tunnel, thus creating multiple opportunities to confound signal return. These unfavorable geologic factors prompted the team to develop seismic-acoustic technologies, to locate tunneling activity rather than the tunnels themselves.

INITIAL EXPERIMENTS

The initial project centered on data collection from a tunnel the team dug at the interface of the compacted silt layers and the unconsolidated coarse sand layer. The sensor array was placed at right angles to the tunnel and data collected over several days. The experimental face was some 6 m from the shaft entrance and just over one meter in surface area (Tucker, McKenna, McKenna, and Mattice, 2007). This data was used to populate the computer algorithms and train the users. Figure 4 shows the typical data signatures collected during the study.

During data collection the rainy season began. This 36-hour rain event provided an excellent opportunity to compare the effect of soil moisture on the propagation and receipt of signals by the array (McKenna and McKenna, 2006). The rain event allowed the team to quantify the signal changes from the full range of mechanical and other sources on a secure facility. The most significant impact was the increase in amplitude. Nearly all signals were detected from greater distances through moist soil than had been observed during the dry season. (see Figures 5 and 6).

Other geochemical impacts on data interpretation can arise as the soils dry out. The evaporation process certainly draws upward long-traveled ground water laden with dissolved salts. The precipitation of sulfate minerals within the upper layers of the soil column attests to the upward migration of mineral-rich solutions.

Beetles and rodents burrow within the sediments and create large galleries. These events are generally observed in the tank ditches surrounding the camp. With extended reach of the data collection array due to the wet environment, some of these signals could become false positives in data interpretation.
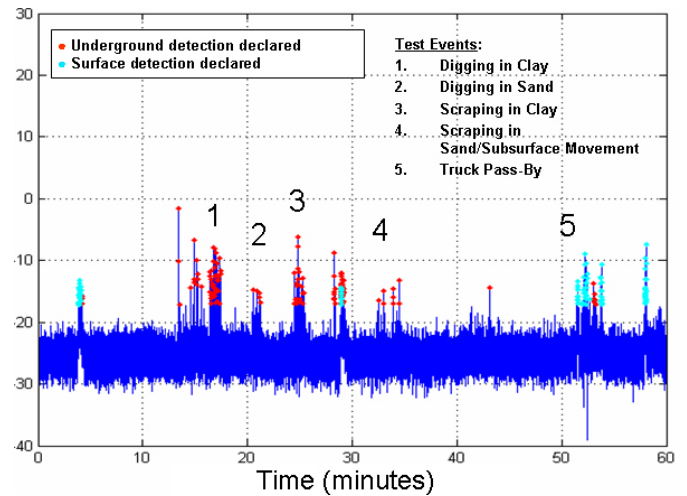

Figure 4. Results of signal processing to automatically differentiate and classify signals originating from the surface and underground.
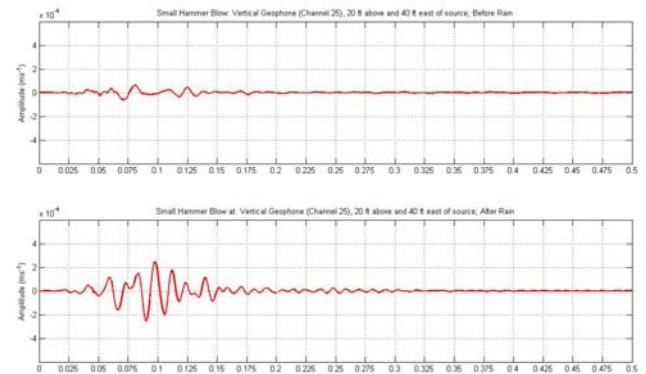

Figure 5. Ambient acoustic noise field before and after 36 hrs of steady precipitation.

The impact on data interpretation would be the number of false positive events and/or an instrument failure. With this new set of data, a better algorithm can be constructed that takes the local meteorological impacts. It is important to remember that the signal signature remains the same, just the definition or amplitude changes.
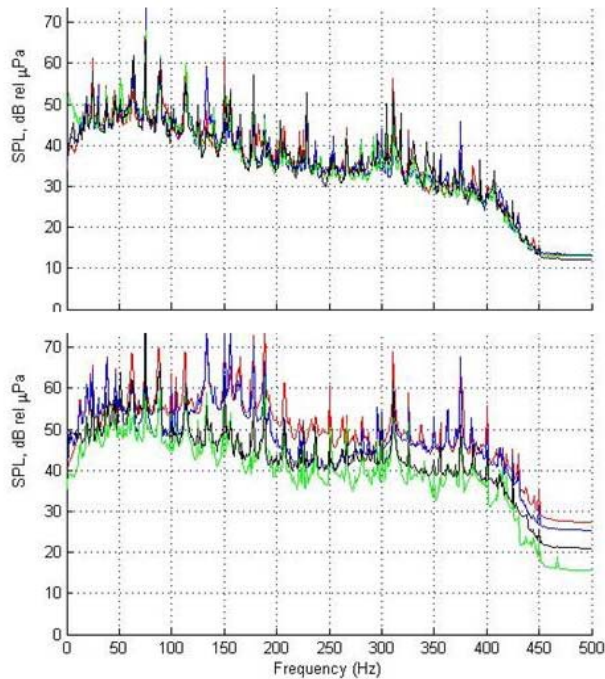
Figure 6 The different curves represent different locations from a diesel generator lying on (but not bolted to) a concrete pad. The top plot is before, and the bottom trace is after the meteorological event. All the data show an increase in amplitude (10 to15 dB up to 450 Hz) due to the increase in the stiffness of the soil, but the change is variable. Data are from microphones, and were collected before and after 36 hr of precipitation

The team is using a detailed soil analysis sampling protocol to better characterize and thus understand the sedimentary environment. During the 2008 sampling season, trenches were dug at two test site facilities within which a block of one wall was selected for sampling. Ten cm deep drive cylinders were used to collect in situ samples. The soil around the cylinders was carefully removed and saved for further analysis. The collection process continued to a depth of two meters (figure 7).

A similar collection mission was completed at a sample location in another desert environment. At this site, the high water table made collecting a bit more challenging. There were numerous fresh water shells and fragments observed within the sediments indicating ponds and/or a changing river course over time. The other significant change was the occurrence of halite (NaCl) crystals within the soil column. Figure 8 shows the sample trench and the sample collection block from which the individual layers were removed.

Similar studies were conducted at a site in the US that contains wind and fluvial sediments deposited within a

Figure 7. The top panel shows the drive cylinders before emplacement. The middle panel show the emplaced cylinders. The bottom panel shows the cylinders just before being removed from the sample layer.

large basin environment. These geochemical and geological studies from different areas will compliment each other despite the distance.

ARRAY AROUND THE CAMP

The physical tests and the soil analysis indicated that a seismic and acoustic array could be installed around a facility and automated processes could be used to filter out the vast majority of the energy sources while still differentiating the signals of interest that were likely tunnels being constructed or tunnels being used.

Commercial off the shelf geophones were emplaced around compounds where tunnels had been found. Sensors were placed in pairs (one deep and one shallow) every 12.5 meters covering the entire perimeter. In this configuration, tunnels would be detected as they approached a compound perimeter from either the inside or the outside, but tunnels that were started well within

Figure 8. Trench at second site. The sampling cell is on the right side of the trench. Note the water at about 1.7 m depth.

a side compound would not be immediately detectable due to the range of the signals. The geophones were connected to a buried cable that circled the compound. A control module (Figure 9) was established where the signals were digitized and GPS timed before being relayed to a local processing facility via copper Ethernet lines. Once the system was installed around a compound, the only visible signature was the control module, and it appeared as just one more electrical panel box to the casual observer.

Placing the geophones in pairs was crucial to discriminating between deep and shallow energy sources. Acoustic sensors were placed at regular intervals to help filter out the huge amount of surface background noise from sources that included vehicles, generators, rotary wing aircraft, explosions, and conversations.

After the signal was digitized, it went through an OCONUS filter to determine which signals have characteristics similar to the signals of interest. Then statistics of these signals were computed to reduce the amount of data sent COUNS via a satellite uplink. The data received CONUS went through a set of sophisticated algorithms, this again reduced the data the analyst needed to review. The signals that remained were called areas of interest. The filtering processes

significantly reduced the amount of data that needed to be reviewed by a human, but still the most important part of the system was a human analyst. Each area of interest was reviewed by a trained analyst to determine what kind of energy source produced the signal, whether the signal was generated by threat activity (i.e. digging with a hand tool, scrapping of tools against wall or floor) or clutter activity (e.g., construction, vehicle traffic, or generators). This was completed by looking and listening to sections of the digitized signal, the human eyes and ears are one of the best pattern recognition systems. The analyst was able to identify these signals by comparing them to signals from the Tunnel Activity Detection System (TADS) signal library. This library included both types of signals, threat activity and clutter

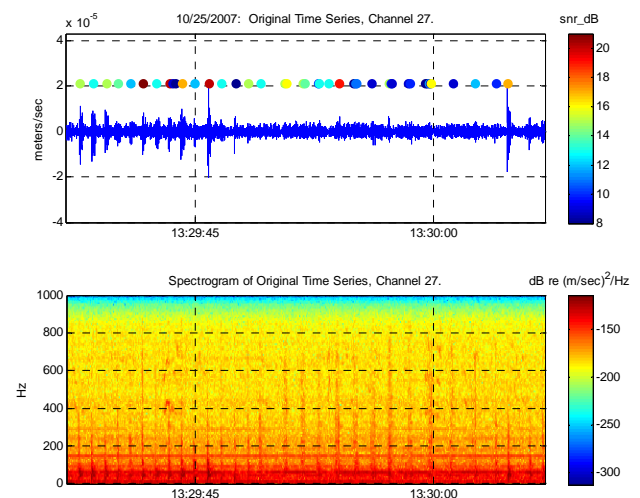Figure 9. Control panel where incoming signals are relayed.

Figure 10: Example of threat activity, the red lines in lower graph (between 10Hz and 400Hz) are impacts with a hand tool, the colored dots above top graph indicate

detections made by the TADS algorithm. Developing the library was a very important step in the development of TADS, it allowed the technical information of signal source identification to be easily passed from an experienced analyst to another analyst.

After an analyst identified an area with threat activity, they sent a notification to the appropriate authority at the secure facility. These notifications were vetted to determine if they were actually threats. The results of this process were added to the signal library to further expand our knowledge of the threat.

CONCLUSIONS

The team worked initially on identifying an appropriate technology that could be used to detect the presence of tunneling activities around secure facilities. The most promising was passive seismic/acoustic arrays. Through the second deployment, the team constructed an array around a secure facility. The initial data were added to the more extensive subsequent data and used to "train" the algorithm.

The installation, validation, and transition of this system were an overwhelming success. We went from field test conducted in 2005 to a fully operational system in a combat zone in one generation. Over the first three months of operation and experience, the analyst tasks were reduced by an order of magnitude and the signal processing algorithms were continually improved.

A systematic investigation of the impacts of soil properties on seismic/acoustic wave propagation could benefit further refinement of the algorithm. Effects of density, grain-size distribution, and moisture content are likely to have impacts on signal propagation and attenuation that have not yet been but could be quantified. Development of this system has continued and updated versions are being installed currently both in the United States and overseas.

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